IAQ EXPOSURE OF SLEEPING OCCUPANTS UNDER DIFFERENT RESIDENTIAL VENTILATION CONFIGURATIONS

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Abstract

Ever tried coming up with a witty question at a conference when your baby child kept you up all night? Of all things done at home, sleeping may have the largest impact on your economic potential. On average, people spend about 1/3rd of their lifetime in their bedroom. Most assessment schemes for residential ventilation only look at the total exposure in all spaces within the dwelling. Physiological and sensory response of sleeping persons to IAQ parameters differs from that in the normal wake state, for which the commonly used performance indicators are developed. Therefore, the exposure within the dwelling should be broken down into exposure in living and bedroom areas for performance assessment.

This paper assesses the exposure of the occupants of a statistically representative dwelling to human bio-effluents and to humidity under 4 different residential ventilation system configurations with multi-zone simulations. Monte Carlo techniques make it possible to assess the sensitivity of the results. The adopted approach varies the most influential boundary conditions such as wind pressure coefficients and occupancy.

The results demonstrate that the expected exposure to unacceptable air quality in the bedrooms is up to 16 times higher than that in the rest oft he dwelling. The results will be used as boundary conditions for experimental investigations on the physiological response to IAQ exposure.

Keywords: IAQ, demand control, residential, bedroom, sleep

1 Introduction

Most assessment schemes for residential ventilation are based on the total exposure in the dwelling in question. However, as we tend to allocate specific spaces for each specific activity in our home, the living pattern of the occupants is very determent and leads to a different exposure pattern in each type of space within the dwelling. Time-use studies (Basner, 2007, Glorieux, 2008) indicate that up to 70% of the time the average western human is in his dwelling, is spent in the bedroom. Physiological and sensory response of sleeping persons to IAQ parameters differs from that in the normal wake state, for which the commonly used performance indicators are developed (Laverge, 2011). The most important drawback of the assessment parameters used traditionally in ventilation standards - eg.(CEN, 2004) - is that they are based on the Perceived Air Quality (PAQ) theorem (Fanger, 1988). It is quite clear that one will not ‘perceive’ the air quality in the same way while asleep or, to put it differently, in a semi-conscious state. Therefore, the exposure within the dwelling should be broken down into exposure in living and bedroom areas for performance assessment.

In this paper, multi-zone simulation (Dols, 2001) was used to assess the expected exposure of the occupants of a detached house with a mechanical exhaust ventilation system to human bioeffluents. This type of ventilation is the most popular system in the moderate climate region of Europe. Due to constraints related to rising energy prices and concerns with climate change as well as its low cost, the implementation of demand control on this type of systems is becoming more and more common. Therefore, the expected exposure was also assessed under 3 demand control configurations for this system that are available on the market. A Monte Carlo based stochastic analysis (Van Den Bossche, 2007, Furbringer, 1995) was used to make the results representative for a large amount of dwellings.

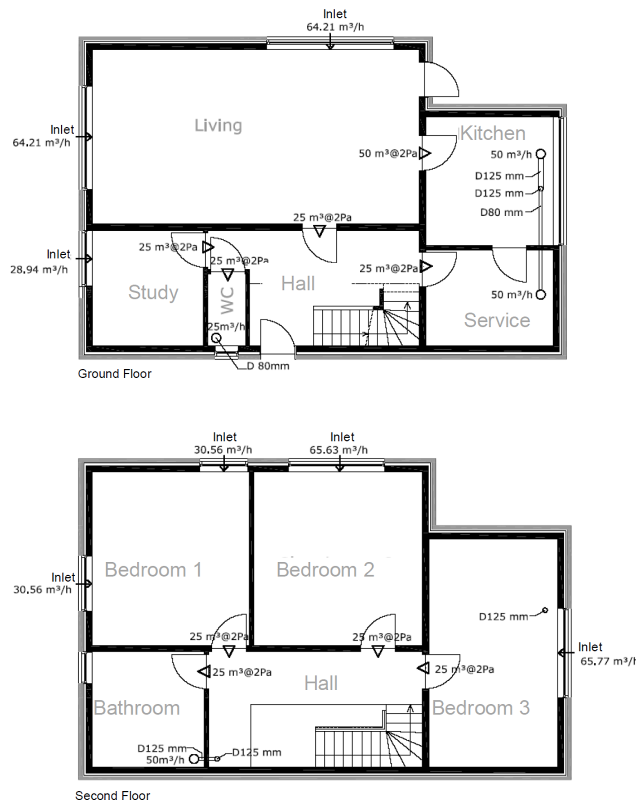
In this paper, the results of these simulations are analysed with regard to their distribution within the dwelling, focussing on the differences between the bedrooms and the rest of the dwelling.

2 Methods

2.1 Building model and sensitivity analysis

The geometry used in the model is based on a detached house that is statistically representative for the average Belgian dwelling. It has been designed for and used in several previous research projects (Verbeeck, 2007, Verbeeck, 2005, Janssens, 2009) and is currently used to assess the performance of residential ventilation systems in the EPBD framework in Belgium (Van Den Bossche, 2007). Table 1. lists the dimensions (m²) of the spaces in the building model. Figure 1 shows the plan of the ground floor and 1st floor of the dwelling.

Each room in the dwelling was modelled as a separate zone. The air leakage of the building was modelled by introducing cracks at both ¼ and ¾ of the height of each wall in order to take into account buoyancy effects. The mechanical exhaust ventilation system is implemented according to the requirements of the Belgian residential ventilation standard (BIN, 1991). This standard imposes design flow rates for the main system components in an exhaust system. In general, the required flow rates are 3.6 m³/h/m² of floor area, with minimum values for wet spaces such as kitchen and bathrooms. The resulting design flow rates are also listed in Table 1.



Figur 1. Ground floor (above) and fist floor (below) of the simulated building.

In the implemented exhaust system all living spaces and bedrooms are equipped with trickle ventilators, which are self-regulating air inlets that maintain a constant volume flow rate at pressure differences higher than 2 Pa. The air is then transferred to the circulation space and from the circulation space to the wet spaces through transfer grilles in the interior doors, where the vent holes are located that are connected to the exhaust fan with circular ducting. The components and their design flow rates are shown in Figure 1.

One of the main problems with simulation models is the uncertainty on input data, despite the fact that the sensitivity of the results to variation in the input data may be very high. A lot of variables have a distinct influence on the performance of the system and consequently the performance of the system will be different for each set of parameters. Large sensitivity to input uncertainty often appears near equilibrium situations which occur for specific values of structural parameters or weather conditions (Furbringer, 1999, Furbringer, 1995).

To prevent this input dependency of the results, the Monte-Carlo (MC) approach, as proposed by Van Den Bossche et al. (Van Den Bossche, 2007), has been used in this study. In this approach, instead of fixing 1 value for each input data, a distribution is determined for the key parameters and multiple simulations are carried out with different values of these parameters. According to Furbringer (Furbringer, 1999, Furbringer, 1995) convergence can be reached within 100 simulations if the amount of input parameters is limited.

As a consequence of the Monte-Carlo approach, the results represent the expected exposure for 334 individual occupants over an average heating season. A detailed overview of the modelling assumptions and the parameter sets that have been used in the simulations, see (Laverge, 2010).

***Table 1**: Floor Area (m^2) and design supply/exhaust air flow rates (m^3/h) of the spaces in the dwelling*

Ground Floor	*Area*	*Supply*	*Exhaust*
Living room	35.7	128.4	
Office	8	28.9	
Kitchen	10.2		50
Service room	7.7		50
Toilet	1.7		25
Hallway	28.1		
First Floor			
Bedroom 1	17	61.1	
Bedroom 2	18.2	65.6	
Bedroom 3	18.3	65.8	
Bathroom	8		50
Hallway	28.1		

2.2 Assessment parameter

Through the correlation between excess CO2 concentration and mean percentage of dissatisfied (CEN 1998) and Fanger's Perceived Air Quality approach (Fanger, 1988), excess CO2 concentration (concentration above the outdoor concentration) is now widely accepted as a proxy for perceived indoor air quality (CEN 2004), especially if the main pollution sources are related to the human metabolism. The production of CO2 within the model is only related to the occupants' metabolism and corresponds to their whereabouts. The production rate is, in accordance with EN 15251 (CEN, 2005), fixed at 19 l/h for an adult performing light work and 12 l/h for an adult at rest. A background outdoor concentration of 350 ppm is assumed.

Within this paper, the excess CO_2 concentration will be used as the assessment parameter for the indoor air quality. As was discussed above, the usability of this parameter for a dormant subject is debatable, but due to lack of a better alternative, excess CO_2 at least provides an indication of the exposure of the subjects to bio-effluents. It can therefore be considered an indicator for the risk of contamination associated with the breathing. Since the results are based on stochastic modelling and is therefore representative for a large population of cases, the parameter is called 'expected' exposure.

Since the aim of the paper is to compare the expected exposure in the bedrooms with the overall expected exposure and that in the other spaces of the dwelling, two additional assessment parameters are introduced, namely the fraction of the total exposure within a certain IAQ-class that takes place in the bedrooms and the ratio of the relative exposure to a certain IAQ-class (characterized by the occurrence of exposure within the class as a fraction of the total time within the room type) in the bedrooms to that in either the entire dwelling and the other spaces in the dwelling. The IAQ-classes referred to are the IDA classes specified in the EN 13779 (CEN, 2004).

2.3 Demand control

Three different demand control strategies were implemented on the basic exhaust ventilation system that is described in section 2.1. All of the strategies reduce the flow rates when ventilation need is limited in terms of perceived indoor air quality, relative humidity or presence of occupants.

Three of them interact with a single system component (trickle ventilator, vent hole and fan), whereas the 4th interacts with these system components simultaneously. All strategies are abstractions of commercially available systems. Table 2. lists a summary of all strategies.

The first control strategy interacts with an economiser in the vent hole of each 'wet' room (kitchen, toilet, service room and bathroom) and is based on the relative humidity measured in the extracted air. A minimal flow rate of 10 % of the design flow rate for each vent hole is maintained at all times. The flow through the vent hole is increased to the design flow rate if the measured relative humidity is higher than 70 % and is reduced to the minimal flow rate again when it drops below 65 %. Note that the fan is not directly affected by this control strategy. The 70 % setpoint is chosen because it is a marker for elevated mould risk on typical thermal bridges (Isaksson, Viitanen). An EMPD model (Janssen, 2009) is used to simulate moisture buffering in the spaces.

The second strategy interacts only on the exhaust fan and is triggered by presence in either bathroom, toilet or kitchen. The total exhaust flow rate is reduced to 10 % of the design flow rate after 20 minutes of absence in all of these rooms. With the detection of presence in any of these rooms, the exhaust flow rate is increased to the total design flow rate for exhaust again.

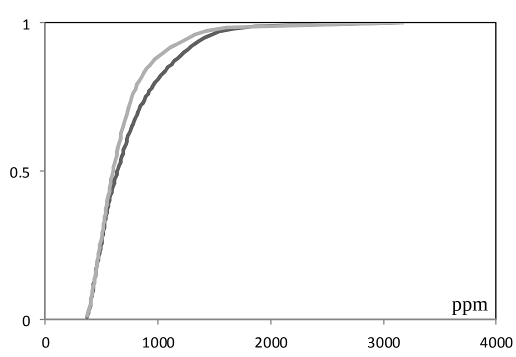
The third strategy interacts with the trickle ventilators (supply) and reduces their opening size according to the CO2 concentration in the room where the trickle ventilator is situated. If the CO2 concentration is below the setpoint of 1000 ppm, the opening size is reduced to 10% of the original size. The 1000 ppm setpoint is popular value in demand control systems on the market (Nielsen). It also corresponds quite well with the concentration that can be expected when an airflow rate of 36 m³/h of fresh air is provided for every occupant in a room, corresponding to the upper limit of the IDA 2 in EN 13779 (CEN, 2004), which is the basis of the design flow rates imposed in the Belgian standard. In this case, extraction flow rates are constant.

***Table 2**: selected demand control strategies*

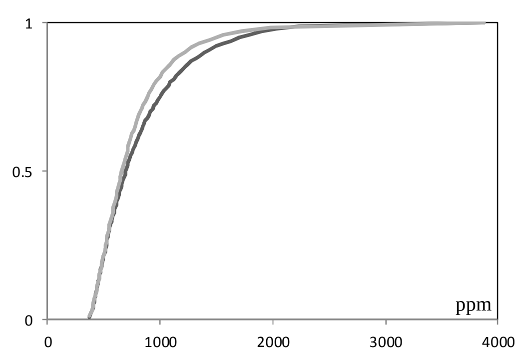
Strategy	*component*	*setpoint*	*band*
1. relative humidity	vent hole	70 %	5 pp
2. presence	fan	-	20 min
3. CO_2	trickle	1000 ppm	-

3 Results

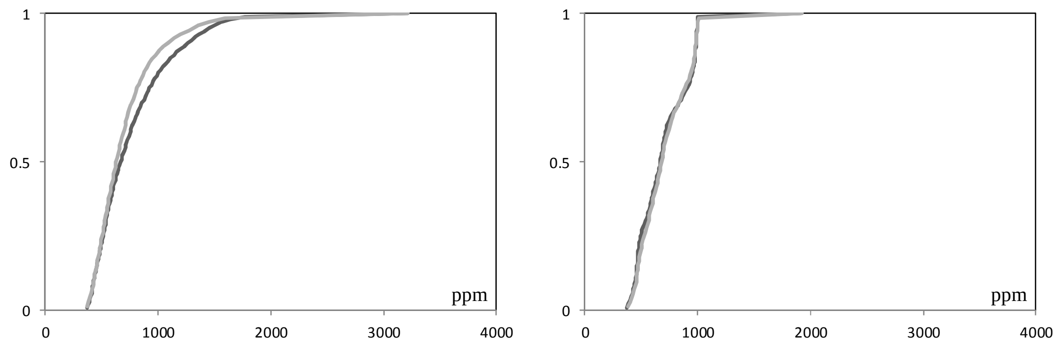
Figure 2. shows the cumulative distribution of the expected exposure of the occupants to CO_2 in all of the 4 simulated systems for both the total time spent in the dwelling and the time spent in the bedrooms based on the simulations. You can clearly see that the exposure in the bedrooms is higher than the overall expected exposure, except for the case where the trickle ventilators are manipulated. Remember that the outdoor concentration is set to 350 ppm.



(a) Continuous flow



(b) humidity controlled



(c) Presence control *(d) supply trickle control*

Figure 2. Cumulative distribution of the exposure to CO_2 (ppm) in the total dwelling (grey) and in the bedroom (black) in the case with continuous flow exhaust ventilation (a), with humidity controlled ventilation (b), with presence control (c) and supply trickle control (d).

The detailed exposure profiles show that the typical exposure to excess CO_2 concentrations in the bedroom is high over a long period in the second half of the night. The results for the other two assessment parameters are shown in Tables 5-6, while Table 3 gives an overview occurrence of the exposure to an air quality within the respective IAQ-classes during the time spent in the dwelling. As was already apparent in Figure 2, the exposure to IAQ generally considered to be unacceptable (IDA 4) is very limited for the system where the trickle ventilators are controlled. This is mainly caused by the fact that by manipulating the trickle ventilators, the buoyancy driven component in the flow dynamics in the building is reduced and the underpressure created by the mechanical exhaust is increased, considerably increasing the proportional influence of the forced flow and reducing the sensitivity to environmental parameters. Likewise, Tables 4-6 demonstrate that this also heavily influences the relative exposure to these high concentrations in the bedrooms. This is explained by the fact that closing the trickle ventilators in the rest of the dwelling at night (due to low CO_2 concentrations in these spaces) will force more air to enter through the bedrooms.

In contrast to these rather positive results in the case with trickle ventilator control, the results for the other cases show that the exposure to bad perceived air quality (IDA 4) is dramatically higher in the bedrooms than in the other parts of the dwelling. Nevertheless, the differences in relative exposure to good perceived air quality (IDA 1 and 2), taking up about 80% of the total exposure time, are less pronounced.

***Table 3**: occurrence of the exposure to an air quality within the respective IAQ-classes for 334 occupants under the 4 ventilation systems*

IAQ-class	*Continuous*	*RH*	*Presence*	*Trickle*
IDA 1 (0-400 ppm)	0.73	0.62	0.68	0.62
IDA 2 (400-600 ppm)	0.14	0.17	0.17	0.19
IDA 3 (600-1000 ppm)	0.09	0.14	0.11	0.19
IDA 4 (> 1000 ppm)	0.04	0.07	0.04	0.00

***Table 4**: fraction of the total exposure to an air quality within the respective IAQ-classes taking place within the bedrooms for 334 occupants under the 4 ventilation systems*

IAQ-class	*Continuous*	*RH*	*Presence*	*Trickle*
IDA 1 (0-400 ppm)	0.47	0.49	0.47	0.54
IDA 2 (400-600 ppm)	0.60	0.5	0.54	0.42
IDA 3 (600-1000 ppm)	0.87	0.65	0.78	0.56
IDA 4 (> 1000 ppm)	0.95	0.87	0.94	0.07

***Table 5**: ratio of the relative exposure to an air quality within the respective IAQ-classes within the bedrooms to that within the entire dwelling for 334 occupants under the 4 ventilation systems*

IAQ-class	*Continuous*	*RH*	*Presence*	*Trickle*
IDA 1 (0-400 ppm)	0.87	0.91	0.88	1.04
IDA 2 (400-600 ppm)	1.1	0.93	1.01	0.8
IDA 3 (600-1000 ppm)	1.6	1.2	1.45	1.08
IDA 4 (> 1000 ppm)	1.75	1.61	1.74	0.13

***Table 6**: ratio of the relative exposure to an air quality within the respective IAQ-classes within the bedrooms to that within the rest of the dwelling for 334 occupants under the 4 ventilation systems*

IAQ-class	*Continuous*	*RH*	*Presence*	*Trickle*
IDA 1 (0-400 ppm)	0.75	0.82	0.77	1.09
IDA 2 (400-600 ppm)	1.25	0.85	1.02	0.65
IDA 3 (600-1000 ppm)	5.52	1.58	3.03	1.18
IDA 4 (> 1000 ppm)	16.13	5.59	12.54	0.06

4 Conclusions

In this paper, the expected exposure to excess CO_2 concentrations in the bedroom of a statistically representative detached house were analysed and compared with the distribution of the expected exposure in the other spaces of the dwelling. The results showed that the relative exposure to unacceptable perceived air quality (IDA 4) is up to 16 times higher in the bedroom than in the rest of the dwelling. Since we spend between 40 and 70% of our time spent at home in the bedroom, this should be subject to improvement. Nevertheless, the relative exposure to good indoor air quality, comprising about 80% of the exposure time, was comparable to that in the rest of the dwelling.

The higher relative exposure to low air quality in the bedrooms can be mainly be explained by the flow dynamics in the whole dwelling. Since the bedrooms are, on average, located on the upper floors of the dwelling, they are more influenced by the counteraction of buoyancy driven flow and mechanical exhaust flow. Therefore, the net fresh air flow in the bedrooms is lower than in the other parts of the dwelling, causing higher concentrations and exposure. Judicious manipulation of the trickle ventilators can redirect the fresh air flow to where it is needed. This is shown in the results of the demand controlled system where the trickle ventilators are manipulated, resulting in a relative exposure to unacceptable perceived air quality (IDA 4) that is about 17 times lower in the bedrooms than in the rest of the dwelling.

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